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PROJECT TITLE : Advanced Computational Aeroacoustics

Methods for Fan Noise Prediction

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PROJECT SUMMARY

Direct computation of fan noise is presently not possible. One of the major difficulties is the geometrical complexity of the problem. In the case of fan noise, the blade geometry is critical to the loading on the blade and hence the intensity of the radiated noise. The precise geometry must be incorporated into the computation. In computational fluid dynamics (CFD), there are two general ways to handle problems with complex geometry. One way is to use unstructured grids. The other is to use body fitted overset grids. In the overset grid method, accurate data transfer is of utmost importance. For acoustic computation, it is not clear that the currently used data transfer methods are sufficiently accurate as not to contaminate the very small amplitude acoustic disturbances. In CFD, low order schemes are, invariably, used in conjunction with unstructured grids. However, low order schemes are known to be numerically dispersive and dissipative. Dispersive and dissipative errors are extremely undesirable for acoustic wave problems. The objective of this project is to develop a high order unstructured grid Dispersion-Relation-Preserving (DRP) scheme. This high order scheme would minimize numerical dispersion and dissipation errors. This report contains the results of the funded portion of the project. An optimized DRP scheme on an unstructured grid has been developed. The scheme is constructed in the wave number space. The characteristics of the scheme can be improved by the inclusion of additional constraints. Stability of the scheme has been investigated. Stability can be improved by adopting the upwinding strategy.

1. PROJECT OBJECTIVES

Fan noise sources are all confined inside a jet engine. Because of this, the requirements on the computation methods for fan noise prediction are very different from those for jet or airframe noise. Jet and airframe noise problems are open domain problems. Being confined inside solid surfaces, fan noise problems are primarily interior domain problems. The presence of confining surfaces leads to the continuous reflection of acoustic waves back into the computation domain. For this reason, care must be exercised in the design of the numerical algorithm for fan noise source computation or simulation.

There are three major challenges in performing direct computation of fan noise. They are :

(a) Moving grid computation

The cutting of the rotor wake by the stator is a major source of fan noise. For an accurate simulation of the wake cutting and sound generation process, it is necessary to compute the flow field with respect to both the fan rotor and stator accurately. For the flow around the fan, the natural computation domain is one that rotates with the blades. As for the stator, the preferred computation domain is one that is fixed to the jet engine coordinates. Thus, one must deal with the situation of relative motion between two different grids adjacent to each other.

(b) Geometrical complexity

The geometry of present day fan engine rotor and stator blades is quite complex. This complexity will increase in the future when blade lean and sweep are incorporated into their design. To handle complex geometry computationally, standard CFD approach is to resort to unstructured grids or body fitted mesh. Unfortunately, both types of grids are designed for use with low order schemes. They are, therefore, not suitable for fan noise

computation. High order nondispersive and nondissipative computation schemes are needed for accurate and efficient acoustic computation and simulation.

(c) Termination boundary condition for ducted domain

If a reasonable size computation domain is used to simulate the fan noise generation processes, the domain will not encompass the entire engine. In other words, one or more of the boundaries of the computation domain will be inside the engine. At such a boundary, a termination boundary condition must be enforced to prevent incoming disturbances to come into the computation domain and, at the same time, allows outgoing disturbances to leave smoothly. Owing to the presence of the duct walls, the wall reflections cause the sound waves to form duct modes. Duct modes are dispersive waves. For dispersive waves, the standard method to construct radiation or outflow boundary conditions through the use of asymptotic solutions is not applicable. There is no known asymptotic solution of constant profile dispersive waves in a ducted domain. Absorbing boundary conditions such as the Perfectly Matched Layer (PML) is also not suitable for a ducted domain with nonuniform flow. There is a need for designing a stable and effective termination boundary condition for ducted problems.

The primary objective of this project is to develop a high order DRP scheme that can be implemented on an unstructured grid. Such a methodology will be able to overcome the problem of moving grid as well as geometrical complexity. In addition, a termination boundary condition for nonuniform mean flow in a ducted domain is to be developed.

2. RESEARCH PROGRAM OF THE PROJECT

The research program of this project consists of two parts. The first part is the development of a new class of advanced CAA methods specifically for fan noise source simulation. The second part involves the application of these methods to the simulation of fan noise generation.

Research plan for the development of a new class of advanced CAA methods consists of the following tasks.

- (a) Develop a new and advanced class of Dispersion-Relation-Preserving high-order, large bandwidth schemes for implementation on unstructured grids. The scheme is to have built-in characteristics suitable for moving grid computation.
- (b) Formulate an artificial selective damping scheme for use on an unstructured grid.
- (c) Develop a set of high quality numerical termination boundary conditions for ducted environment.

Research plan for applications to fan noise source computation consists of the following two tasks.

- (a) Investigate sound generation by the interaction of a gust and a finite thickness cascade with realistic blade geometry and flow conditions.
- (b) Perform time domain simulation of sound generation arising from the cutting of the potential wake of a fan cascade by a stator.

In the original proposal, three years funding was requested and approved. However, due to NASA budget short fall, only the first year was funded. Thus only the first part of the research program was completed. Accordingly, in this report, only the results of the first year work are summarized and reported below.

3. RESEARCH RESULTS

A high resolution, large bandwidth DRP scheme for use on unstructured grids has been successfully developed. In formulating this method, a new way to approximate spatial derivatives by finite difference quotients using the values of the function on the vertices of the unstructured grid was developed. Traditional way of formulating a finite difference quotient is to assume that the mesh size is small, so that the function evaluated at the neighboring points can be expanded by Taylor series. Standard finite difference approximations are found by truncating the Taylor series and then eliminating the unknown first and higher order derivative terms using values of the function on the stencil. Tam and Webb (Journal of Computational Physics, vol.107, pp. 262-281, 1993) have shown that this way of developing finite difference approximation does not yield a good approximation over a wide band of wave numbers.

In developing the new method, the mesh size is assumed to be finite. No Taylor series expansion and truncation are necessary. In formulating the finite difference approximation, focus is on how well the stencil coefficients can be chosen so that the finite difference quotient is a good approximation of the spatial derivative in wave number space in 2 or 3 dimensions. The first step involves the construction of the error of the approximation in wave number space. The stencil coefficients are then determined so that the error of approximation is minimized over a wide band of wave numbers (in two to three dimensions).

In certain situations, it may be desirable to include a formal order of approximation to the finite difference scheme. It turns out, it is possible to incorporate such a need in the new scheme. This is done by including additional constraints in the minimization procedure by which the stencil coefficients are found. The error function is minimized subject to the prescribed constraints using the method of Lagrange multiplier. Numerical results, however, indicate that for a given size stencil, the imposition of

formal order constraints does not necessarily improve the approximation when viewed from the wave number space. Thus it is believed that only low formal order should be imposed.

A computation scheme is useful only if it is numerically stable. Numerical instability can arise when the wave number of the finite difference scheme is complex. This usually occurs for high wave numbers, specifically the grid-to-grid oscillations. Thus it is important for a scheme to have numerical damping over the high wave number range. The numerical damping may be an intrinsic part of the scheme or can be added as artificial selective damping. In the new scheme, it is recommended that the stencil be chosen so that some degree of upwinding is included. Upwinding strategy automatically introduces some numerical damping into the finite difference scheme.

As mentioned above, this project , planned for three years, was funded for only the first year. Application of the method developed to fan noise problems was not carried out. Research effort ceased at the end of the first year.